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DYNAMIC VOLTAGE RESTORER (DVR) FOR VOLTAGE SAG MITIGATION

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ABSTRACT

Voltage sags and swells in the medium and low voltage distribution grid are considered to be the most frequent type of power quality problems based on recent power quality studies. Their impact on sensitive loads is severe. The impact ranges from load disruptions to substantial economic losses up to millions of dollars. Different solutions have been developed to protect sensitive loads against such disturbances but the DVR is considered to be the most efficient and effective solution. Its appeal includes lower cost, smaller size and its dynamic response to the disturbance. This research described DVR principles and voltage restoration methods for balanced and/or unbalanced voltage sags and swells in a distribution system. Simulation results were presented to illustrate and understand the performances of DVR under voltage sags/swells conditions.

INTRODUCTION

Dynamic voltage restores (DVRs) are now becoming more established in industry to reduce the impact of voltage dips on sensitive loads. A voltage dip is commonly defined as any low voltage drop event between 10% and 90% of the nominal RMS voltage, lasting between 0.5 cycles and 1 min. In comparison with interruptions, voltage dips affect a large number of customers and for some cases may cause extremely serious problems. voltage dips are one of the most occurring power quality problems. They occur more often and cause severe problems and economical losses.

There are different ways to mitigate voltage dips, swells and interruptions in transmission and distribution systems. At present, a wide range of very flexible controllers which capitalize on newly available power electronics components are emerging for custom power applications. Among these, the distribution static compensator and the dynamic voltage restorer are the most effective devices; both of them based on the voltage source converter (SVC) principle.

Figure 1 shows a typical DVR series connected topology. The DVR essentially consists of a series inverter (VSI), inverter output filter and an energy storage device connected to the DC link.The basic operation principle of the DVR is to inject an appropriate voltage in series with the supply through injection transformer whenever voltage sag or voltage swell is detected. In addition to voltage sags and swells compensation, DVR can also perform other

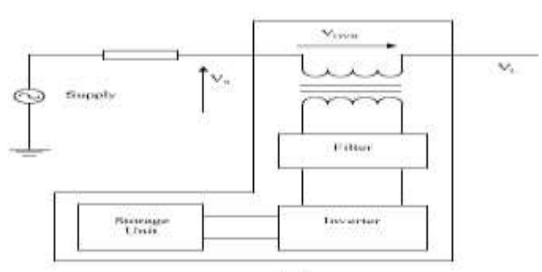

Fig. 1: DVR series connected topology

tasks such as harmonic compensation and Power Factor correction. Compared to the other Custom Power devices, the DVR clearly provides the best economic solution for its size and capabilities.

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This research introduced Dynamic Voltage Restorer (DVR) and its voltage compensation methods.

DYNAMICVOLTAGE RESTORER

A Dynamic Voltage Restorer (DVR) is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. The DVR was first installed in 1996[6]. It is normally installed in a distribution system between the supply and the critical load feeder[7]. Its primary function is to rapidly boost up the load-side voltage in the event of a disturbance in order to avoid any power disruption to that load[8,9]. There are various circuit topologies and control schemes that can be used to implement a DVR. In addition to voltage sags and swells compensation, DVR can also perform other tasks such as: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

The general configuration of the DVR consists of an Injection/Booster transformer, a Harmonic filter, a Voltage Source Converter (VSC), DC charging circuit and a Control and Protection system as shown in Fig. 1.

Conventional DVR Voltage Injection Methods

The possibility of compensating voltage sag can be limited by a number of factors including finite DVR power rating, different load conditions and different types of voltage sag. Some loads are very sensitive to phase angle jump and others are tolerant to it. Therefore, the control strategy depends on the type of load characteristics. There are three distinguishing methods to inject DVR compensating voltage:

Pre-Dip Compensation (PDC)

The PDC method tracks supply voltage continuously and compensates load voltage during fault to pre-fault condition. In this method, the load voltage can be restored ideally, but the injected active power cannot be controlled and it is determined by external conditions such as the type of faults and load conditions. The lack of the negative sequence detection in this method leads to the phaseoscillation in the case of single-line faults. Figure 2 shows the single-phase vector diagram of this method.
According to Fig. 2, the apparent power of DVR is:

$$S_{IDVR} = I_L V_{IDVR} = I_L \sqrt{V_L^2 + V_S^2 - 2V_L V_S \cos(\theta_L - \theta_S)}$$

And the active power of DVR is:

$$P_{IDVR} = I_L (V_L \cos\theta_L - V_S \cos\theta_S)$$

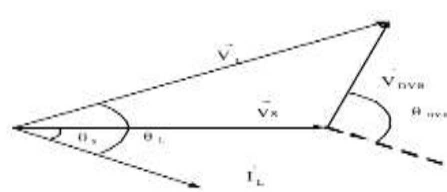

Fig. 2: Single phase vector diagram of the PDC method

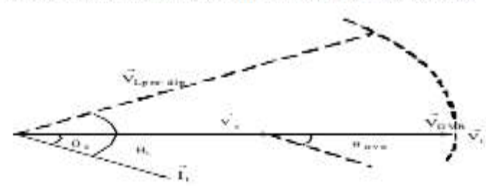

Fig. 3: Single-phase vector diagram of the IPC method

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The magnitude and the angle of the DVR voltage are:

$$V_{1DVR} = \sqrt{V_L^2 + V_S^2 - 2V_L V_S \cos(\theta_L - \theta_S)}$$

$$\theta_{1DVR} = \tan^{-1}\left(\frac{V_L \sin\theta_L - V_S \sin\theta_S}{V_L \cos\theta_L - V_S \cos\theta_S}\right)$$

In-Phase Compensation (IPC)

This is the most used method in which the injected DVR voltage is in phase with the supply side voltage regardless of the load current and the pre-fault voltage as shown in Fig. 3. The IPC method is suitable for minimum voltage or minimum energy operation strategies [10]. In other word, this approach requires large amounts of real power to mitigate the voltage sag, which means a large energy storage device.

The apparent and active powers of DVR are:

$$S_{2DVR} = I_L V_{DVR} = I_L (V_L - V_S)$$

$$P_{2DVR} = I_L V_{DVR} \cos\theta_S = I_L (V_L - V_S) \cos\theta_S$$

The magnitude and the angle of the DVR voltage are:

$$V_{2DVR} = V_L - V_S$$
$$\theta_{2DVR} = \theta_S$$

In-Phase Advance Compensation (IPAC)

Pre-Dip and in-phase compensation method must inject active power to loads to correct voltage disturbance. However, the amount of possible injection active power is confined to the stored energy in DC link, which is one of the most expensive components in DVR. Due to the limit of energy storage capacity of DC link, the DVR Restoration time and performance are confined in these methods.

For the sake of controlling injection energy, in phase advance compensation method was proposed.

The injection active power is made zero by means of having the injection voltage phasor perpendicular to the load current phasor. This method can reduce the consumption of energy stored in DC link by injecting reactive power instead of active power. Reducing energy consumption means that ride-through ability is increased when the energy storage capacity is fixed. On the other hand, the injection voltage magnitude of in phase advance compensation method is larger than those of pre-dip or in-phase compensation methods and the voltage phase shift can cause voltage waveform discontinuity, inaccurate zero crossing and load power swing. Therefore, in phase advance compensation method should be adjusted to the load that is tolerant to phase angle jump, or transition period should be taken while phase angle is moved from pre-fault angle to advance angle.

In short, IPAC method uses only reactive power and unfortunately, not al1 the sags can be mitigated without real power, as a consequence, this method is only suitable for a limited range of sags.

IMPORTANCE OF POWER QUALITY

Power quality has assumed increasing importance in view of the widespread use of power electronic equipment. For reactive var compensation, in addition to shunt capacitors and reactors, static var compensators (SVCs) are used. They are also used to solve several power quality problems—for reducing voltage sags, over voltages after fault clearing, voltage regulation, negative sequence voltages, etc. In some cases, harmonics can cause mis-operaton of the protective equipments, contributing to a reduction in power quality. Harmonic filters are used to absorb undesirable harmonics. Further, with the deregulation of the power industry, competitive pressures force electric utilities to cut costs, which sometimes affects power quality and reliability. Hence, it must be ensured by suitable regulations that customers do not suffer from reduced power quality and reliability. This chapter covers issues of power quality, and later chapters deal with other topics such as SVCs, harmonics, filters and shunt capacitors, and reactors for reactive var compensation.

The aim is to introduce the concept of power quality and its importance, and explain the common terms used in describing power quality. Any person who is interested in pursuing this subject further can find material from the references at the end of this chapter. The term power quality is rather nebulous and may be associated with reliability by electric utilities. However, equipment manufacturers can interpret it rather differently, referring to those characteristics of power supply that enable the equipment to work properly. Recently, people working in the field appear to have agreed on the following definition of a power quality problem. A power quality problem is any occurrence manifested in voltage, current, or frequency deviation that results in failure or mis-operation of customer equipment. Although people talk of "power quality quite often, they are actually referring to "voltage quality" because most of the time the controlled quantity is voltage. Another term that is used to indicate the non availability of electricity supply to consumers because of sustained interruptions is reliability.

COMMON DISTURBANCES IN POWER SYSTEMS

The common disturbances in a power system are
a. Voltage sag
b. Voltage swell
c. Momentary interruptions
d. Transients
e. Voltage unbalance
f. Harmonics
g. Voltage fluctuations

SHORT-DURATION VOLTAGE VARiATiON

A voltage sag (dip) is defined as a decrease in the root-mean-square (rms) voltage at the power frequency for periods ranging from a half cycle to a minute.11 It is caused by voltage drops due to fault currents or starting of large motors. Sags may trigger shutdown of process controllers or computer system crashes. A voltage swell is defined as an increase up to a level between 1.1 and 1.8 pu in rms voltage at the power frequency for periods ranging from a half cycle to a minute.
An interruption occurs when the supply voltage decreases to less than 0.1 pu for a period of time not exceeding 1 min. Interruptions can be caused by faults, control malfunctions, or equipment failures.

Long-Duration Voltage Variations

An under voltage is a decrease in the rms ac voltage to less than 90% at the power frequency for a duration longer than 1 min. These can be caused by switching on a large load or switching off a large capacitor bank.1,11 Under voltages are sometimes due to a deliberate reduction of voltage by the utility to lessen the load during periods of peak demand. These are often referred to by the nontechnical term brownout. An under voltage will lower the output from capacitor banks that a utility or customer will often install to help maintain voltage and reduce losses in the system by compensating for the inductive nature of many conductors and loads.

An overvoltage is an increase in the rms ac voltage to a level greater than 110% at the power frequency for a duration longer than 1 min. These are caused by switching off a large load or energizing a capacitor bank. Incorrect tap settings on transformers can also cause under voltages and over voltages. As these can last several minutes, they stress computers, electronic controllers, and motors. An overvoltage may shorten the life of power system equipment and motors.

TRANSIENTS

Impulsive Transients

An impulsive transient is a sudden non power frequency change in the steady-state condition of voltage or current, or both, which is unidirectional in polarity (either positive or negative). Some people use the term surge to describe an impulsive transient, whereas others employ it to denote any transient. Because this is ambiguous, it is better to avoid its use without qualification.

Impulsive transients are normally characterized by their rise and decay times. They can also be described by their spectral content. For example, a 1.2-/50-ms 4000-V impulsive transient rises to its peak value of 4000 V in 1.2 ms, and then decays to half its peak value in 50 ms. The most common cause of impulsive transients is lightning.

Oscillatory Transients

An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content.

Voltage IMBALANCE

Voltage imbalance (unbalance) is defined as the ratio of a negative- or zero-sequence component to a positive-sequence component. The voltage imbalance in a power system is due to single-phase loads. In particular, single-phase traction loads connected across different phases produce negative-phase-sequence voltages, which in many cases have to be reduced to less than 2% with the help of SVCs. Severe voltage imbalance can lead to derating of induction motors because of excessive heating. Voltage imbalance can also occur from a blown fuse on one phase of a three-phase bank. There are occasions when a severe voltage imbalance greater than 5% can occur from single-phasing conditions. Voltage or current imbalance is estimated sometimes (less commonly) using the Following definition:

Maximum deviation from the average of the three-phase voltages (or currents) divided by the average of the three-phase voltages (or currents)

HARMONICS

When a nonlinear load is supplied from a supply voltage of 60-Hz or 50-Hz frequency, it draws currents at more than one frequency, resulting in a distorted current waveform. Fourier analysis of this distorted current waveform resolves it into its fundamental component and different harmonics. Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency (usually 60 Hz or 50 Hz in power systems).

Harmonic distortion is a growing concern for many customers and the utilities because of increasing application of power electronics equipment. The nonlinear harmonic-producing devices can be modeled as current sources that inject harmonic currents into the power system.

We will discuss in detail in a later chapter the sources and disadvantages of harmonics.In this section, we will limit our discussion to some of the common terms associated with harmonic distortion.Harmonic voltage distortion (Un): The rms value of a harmonic voltage of order n, expressed as a percentage of the rms value of the fundamental component. Total harmonic voltage distortion (THD): This is calculated from the expression THD = $\sqrt{\Sigma}$ (Un)2 and expressed as a percentage of the fundamental component. Similarly, harmonic current distortion and total harmonic current distortion can be defined. Harmonic distortion levels can be characterized by the complete harmonic spectrum with magnitude and phase angles of each individual harmonic component.

When dealing with harmonic current quantities, the total harmonic current distortion value can be misleading. Some harmonic-producing loads (for example, adjustable speed drives) will exhibit high total harmonic current distortion values under light load conditions. This is not a significant concern because the magnitude of the harmonic current is low even though its relative distortion is high. To handle this concern, IEEE Std 519-1992 defines another term, total demand distortion (TDD). This is the same as total harmonic current distortion except that the distortion is expressed as a percentage of some rated load current instead of the fundamental current magnitude. Some authors use harmonic current values in amps rather than as a percentage of the fundamental current magnitude. IEEE Std 519-1992 provides guidelines for harmonic voltage and current distortion levels on transmission and distribution circuits.12

Interharmonics

Inter harmonics are defined as frequency components of voltages or currents that are not an integer multiple of the normal system frequency (e.g., 60 or 50 Hz). The main sources of inter harmonics are static frequency converters, cyclo converters, induction motors, and arcing devices. Power line carrier signals can be considered as inter harmonics. The effects of inter harmonics are not well known but have been shown to affect power line carrier signaling and induce visual flicker in display devices such as cathode ray tubes (CRTs).Two other phenomena in power electronic devices contribute to waveform distortion. These are (1) dc offset and (2) notching, which we shall explain in the following sections.

DC OFFSET

The presence of a dc voltage or current in an ac power system is termed dc offset.1,11 This phenomenon can occur from the effect of half-wave rectification or as the result of a geomagnetic disturbance. Half-wave rectification is sometimes used in light dimmer circuits and TV power supplies. Direct current in alternating current networks can cause (1) transformer saturation with consequent increased losses, additional heating, and reduction in transformer life, and (2) the electrolytic erosion of grounding electrodes.

NOTCHING

Three-phase converters that convert ac to dc require commutation of the alternating current from one phase to another. During this period, there is a momentary short circuit between the two phases. This causes a periodic voltage disturbance, which is called notching.1,11 The frequency components associated with notching can be quite high and may not be characterized with the help of measurement equipment normally used for harmonic analysis. The severity of the notch at any point in the system is determined by the source impedance and isolating inductance between the converter and the point being monitored.

VOLTAGE FLUCTUATIONS

Loads that exhibit continuous, rapid variations in load current can cause voltage variations erroneously referred to as flicker. ANSI C84.1-1992 recommends that the system voltages should lie in the range 0.9–1.1 pu.IEC 1000-3-3 (1994) defines various types of voltage fluctuations. We will concentrate on voltage fluctuations of the IEC 1000-3-3 (1994), Type (d). This type is characterized as systematic variations of voltage envelopes or a series of random voltages.

Arc furnaces are the most common cause of voltage fluctuations in the transmission and distribution system. Voltage fluctuations are defined by their rms magnitude expressed as a percentage of the fundamental magnitude.1,11 They are the response of the power system to the varying load, and light flicker is the response of the lighting system as observed by the human eye. Even though flicker is caused by voltage fluctuations, some authors use the term "voltage flicker" to represent either of these terms.

Voltage fluctuations generally appear as a modulation of the fundamental frequency. Hence, the magnitude of voltage fluctuations can be obtained by demodulating the waveform to remove the fundamental frequency and then measuring the magnitude of the modulation components. Typically, magnitudes as low as 0.5% can result in perceptible light flicker if the frequencies are in the range of 6–8 Hz.

Power Frequency Variations

At any instant, the frequency depends on the balance between the load and the capacity of the available generation.1,11 When dynamic balance changes, small changes in frequency occur. In modern interconnected power systems, frequency is controlled within a tight range as a result of good governor action. Frequency variations beyond ±0.1 Hz are likely to occur under fault conditions or from the loss of a major load or generating unit. However, in isolated systems, governor response to abrupt load changes may not be adequate to regulate them within the narrow bandwidth required by frequency-sensitive equipment.

Voltage notching can sometimes cause frequency or timing errors on power electronic machines that count zero crossings to derive frequency or time. The voltage notch may produce additional zero crossings that can cause frequency or timing errors and affect the performance of digital electric clocks.

Many other power quality terms and their definitions are listed in References 1 and 11 to promote standardization in the power quality literature.

Introduction to DVR

The technological advancements have proven a path to the modern industries to extract and develop the innovative technologies within the limits of their industries for the fulfillment of their industrial goals. And their ultimate objective is to optimize the production while minimizing the production cost and thereby achieving maximized profits while ensuring continuous production throughout the period.

As such a stable supply of un-interruptible power has to be guaranteed during the production process. The reason for demanding high quality power is basically the modern manufacturing and process equipment, which operates at high efficiency, requires high quality defect free power supply for the successful operation of their machines [1]. More precisely most of those machine components are designed to be very sensitive for the power supply variations. Adjustable speed drives, automation devices, power electronic components are examples for such equipments [2,3].

Failure to provide the required quality power output may sometimes cause complete shutdown of the industries which will make a major financial loss to the industry concerned [4,5,6]. Thus the industries always demands for high quality power from the supplier or the utility. But the blame due to degraded quality cannot be solely put on to the hands of the utility itself [7]. It has been found out most of the conditions that can disrupt the process are generated within the industry itself. For example, most of the non-linear loads within the industries cause transients which can affect the reliability of the power supply [8,9]. Following shows some abnormal electrical conditions caused both in the utility end and the customer end that can disrupt a process [7,10].

1. Voltage sags
2. Phase outages
3. Voltage interruptions
4. Transients due to Lighting loads, capacitor switching, non linear loads, etc..
5. Harmonics

As a result of above abnormalities the industries may undergo burned-out motors, lost data on volatile memories, erroneous motion of robotics, unnecessary downtime, increased maintenance costs and burning core materials especially in plastic industries, paper mills & semiconductor plants [8,11].

Among those power quality abnormalities voltage sags and surges or simply the fluctuating voltage situations are considered to be one of the most frequent type of abnormality [4,12,13]. Those are also identified as short term under/over voltage conditions that can last from a fraction of a cycle to few cycles [3,4,11]. Motor start up, lightning strikes, fault clearing, power factor switching are considered as the reasons for fluctuating voltage conditions [7].As the power quality problems are originated from utility and customer side, the solutions should come from both and are named as utility based solutions and customer based solutions respectively [3]. The best examples for those two types of solutions are FACTS devices (Flexible AC Transmission Systems) and Custom power devices. FACTS devices are those controlled by the utility, whereas the Custom power devices are operated, maintained and controlled by the customer itself and installed at the customer premises [7].Both the FACTS devices and Custom power devices are based on solid state power electronic components [7]. As the new technologies emerged, the manufacturing cost and the reliability of those solid state devices are improved; hence the protection devices which incorporate such solid state devices can be purchased at a reasonable price with better performance than the other electrical or pneumatic devices available in the market [5]. Uninterruptible Power Supplies (UPS), Dynamic Voltage Restorers (DVR) and Active Power Filters (APF) are examples for commonly used custom power devices. Among those APF is used to mitigate harmonic problems occurring due to non-linear loading conditions, whereas UPS and DVR are used to compensate for voltage sag and surge conditions [1,5,12,15].

The control of a Dynamic voltage restorer for single phase voltage sags has been studied. Voltage sag may occur from single phase to three phases. But it has been identified single phase voltage sags are the commonest and most frequent in Sri Lanka. Therefore the industries that use three phase supply will undergo several interruptions during their production process and they are compelled to use some form of voltage compensation equipment. In this research it was found that the most common voltage compensation equipment used in Sri Lanka is the UPS; though it's considered to be an expensive alternative to move towards a full UPS system. This is the basic reason to carry out this research in that particular area and focused into single phase voltage sags.

A new control technique to detect and compensate for the single phase voltage sags was developed and simulated using the EMTDC/PSCAD software. Combination of both the pre-sag and in-phase compensation techniques was used in the above developed control to optimize the real power requirement during compensation. In the said control technique the system generates a random reference voltage waveform with the nominal voltage amplitude and the frequency with automated synchronising control. Once the DVR is connected to the system, the phase angle of this reference signal is synchronized with the supply voltage phase angle by continuously monitoring the reference phase angle using a feed back synchronising control loop. Then by comparing this reference voltage waveform with the measured voltage waveform, any occurrence of voltage abnormalities was detected as an error. As the system detect any voltage sags as error, the power circuit in the DVR generates a voltage waveform to compensate for the voltage sag. The design of the power circuit parameters and the control circuit is discussed in the preceding chapters in detail. The simulation results show the very good performance of the controller. One problem was notified as the internal voltage drop of the DVR and it responds when harmonics presents in the supply voltage by becoming the injected voltage being non sinusoidal even under normal operating conditions. However these cases were checked in the simulation. The simulation results show that at the normal operating conditions, the injected voltage becomes less and their affect on the load voltage due to distortion is less. Therefore this thesis has contributed a strong
knowledge to the research and development targeting industrial application to compensate the single-phase voltage sags.

Voltage sags and surges

The most frequent power quality associated problem in the distribution network is voltage sags and surges and are shown in Figure 2.1 below [2,18].

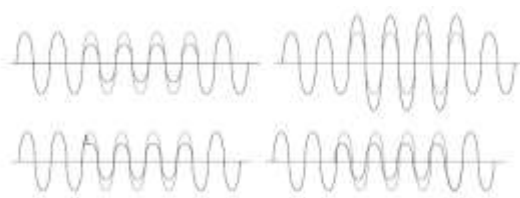

Figure 2.1: top left - Voltage sag occurs at the zero crossing point & without a phase shift
top right - Voltage surge occurs at zero crossing point & without a phase shift
bottom left - Voltage sag not at the zero crossing point & without a phase shift
bottom right - Voltage sag at zero crossing point with a phase shift

Voltage sag/surge can simply be defined as a sudden increase/decrease in the rms voltage with duration of half a cycle to few cycles. In addition to the magnitude change of the supply voltage, there can be a phase shift during the voltage sag / surge as shown in Figure 2.1 [11,13]. The magnitude of the voltage sag will depend on the fault type and the location and also on the fault impedance [19]. The duration of the fault depends on the performance of the relevant protective device [3].Further it has been found that the voltage sags with magnitude 70% of the nominal value are more common than the complete outages [35]. Sags and surges can be identified by the voltage magnitude and the time duration it prevails. IEEE 519-1992, IEEE 1159-1995 describes it as in Table 2.1 [10].

Disturbance	Voltage	Duration
Voltage Sag	0.1 – 0.9 pu	0.5 – 30 cycle
Voltage Swell	1.1 – 1.8 pu	0.5 – 30 cycle

Table 2.1 : IEEE definitions for the voltage sags and swells

For a particular disturbance (voltage sag or swell), if the voltage and time duration it remains is within the range given in Table 2.1, the custom power devices are the optimized solution to overcome the problem and compensate for the abnormality during the time period it prevails [16].

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Custom Power Devices

The most common custom power devices to compensate for the voltage sags and swells are the Uninterruptible Power Supplies (UPS), Dynamic Voltage Restorers (DVR) and Active Power Filters (APF) with voltage sag compensation facility.

Among those the UPS is the well known. DVRs and APFs are less popular due to the fact that they are still in the developing stage, even though they are highly efficient and cost effective than UPSs [3,14,21]. But as a result of the rapid development in the power electronic industry and low cost power electronic devices will make the DVRs and APFs much popular among the industries in the near future [1,22].

DVR and APF are normally used to eliminate two different types of abnormalities that affect the power quality. They are discussed based on two different load situations namely linear loads and non-linear loads. The load is considered to be a linear when both the dependent variable and the independent variable shows linear changes to each other. Resistor is the best example for a linear device. The non-linear load on the other hand does not show a linear change. Capacitors and inductors are examples for non-linear devices.

(a) When the supply voltage/current consists of abnormalities, while the load is linear:

In this case the custom power device together with the defected supply should be capable of supplying a defect free voltage/current to the load. To be precise the device should be able to supply the missing voltage/current component of the source. A reliable device that can be used for the above case (for voltage abnormalities) is the DVR. It compensates for voltage sags/swells either by injecting or absorbing real and reactive power [15].

(b) Power supplied is in normal condition with a non linear load:

When non-linear loads are connected to the system, the supply current also becomes non-linear and this will cause harmonic problems in the supply waveform. In such situation to make the supply current as sinusoidal, a shunt APF is connected [8].This APF injects/absorbs a current to make the supply current sinusoidal. Hence the supply treats both the non-linear load and the APF as a single load, which draws a fundamental sinusoidal current [23,24].

Figures 2.2a and b show the basic function of the DVR and the shunt APF.

Figure 2.2a & b: Basic operation of DVR (left) and APF (right)

From Figures 2.2a, b and the references [11,15,23,25] it is clear that the DVR is series connected to the power line, while APF is shunt connected.

Among the custom power devices, UPS and DVR can be considered as the devices that inject a voltage waveform to the distribution line. When comparing the UPS and DVR; the UPS is always supplying the full voltage to the load irrespective of whether the wave form is distorted or not. Consequently the UPS is always operating at its full power. Whereas the DVR injects only the difference between the pre-sag and the sagged voltage and that also only during the sagged period. Thus DVR operating losses and the required power rating are very low compared to the UPS. Hence DVR is considered as a power efficient device compared to the UPS [12,22,26]

Structure of the DVR

The DVR basically consists of a power circuit and a control circuit. Control circuit is used to derive the parameters (magnitude, frequency, phase shift, etc…) of the control signal that has to be injected by the DVR. Based on the control signal, the injected voltage is generated by the switches in the power circuit [11]. Further power circuit describes the basic structure of the DVR and is discussed in this section. Power circuit mainly comprising of five units as in Figure 2.3 [1,3,11].

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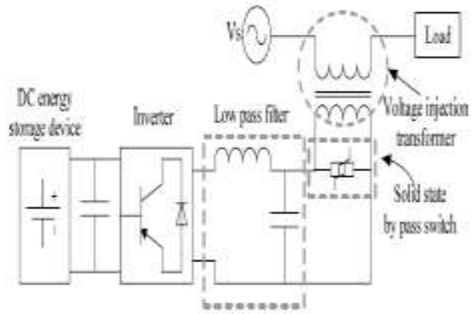

Figure 2.3: DVR Power circuit

DVR operating states

During a voltage sag/swell on the line

The DVR injects the difference between the pre-sag and the sag voltage, by supplying the real power requirement from the energy storage device together with the reactive power. The maximum injection capability of the DVR is limited by the ratings of the DC energy storage and the voltage injection transformer ratio. In the case of three single-phase DVRs the magnitude of the injected voltage can be controlled individually. The injected voltages are made synchronized (i.e. same frequency and the phase angle) with the network voltages [10].

During the normal operation

Since the network is working under normal condition the DVR is not injecting any voltages to the system. In that case, if the energy storage device is fully charged then the DVR operates in the standby mode or otherwise it operates in the self charging mode. The energy storage device can be charged either from the power supply itself or from a different source [11,9].

DVR compensation techniques

The compensation control technique of the DVR is the mechanism used to track the supply voltage and synchronized that with the pre-sag supply voltage during a voltage sag/swell in the upstream of distribution line. Generally voltage sags are associated with a phase angle jump in addition to the magnitude change [11].Therefore the control technique adopted should be capable of compensating for voltage magnitude, phase shift and thus the wave shape. But depending on the sensitivity of the load connected downstream, the level of compensation of the above parameters can be altered. Basically the type of load connected influences the compensation strategy. For example, for a linear load, only magnitude compensation is required as linear loads are not sensitive to phase angle changes [11,13].

Further when deciding a suitable control technique for a particular load it should be considered the limitations of the voltage injection capability (i.e. the rating of the inverter and the transformer) and the size of the energy storage device [11].

Compensation is achieved via real power and reactive power injection. Depending on the level of compensation required by the load, three types of compensation methods are defined and discussed below namely pre-sag compensation, in-phase compensation and energy optimization technique.

The circuit for a simple power system with a DVR is shown in Figure 2.9 below. The supply voltage, Load voltage, Load current and the voltage injected by the DVR are denoted by Vs , Vload , Iload and VDVR respectively.

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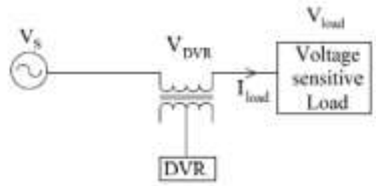

Figure 2.9: Simple power system with a DVR

When the system is in normal condition, the supply voltage (Vs) is identified as pre-sag voltage and denoted by Vpre-sag. In such situation since the DVR is not injecting any voltage to the system, load voltage (Vload) and the supply voltage will be the same.
During voltage sag, the magnitude and the phase angle of the supply voltage can be changed and it is denoted by Vsag. The DVR is in operative in this case and the voltage injected will be VDVR. If the voltage sag is fully compensated by the DVR,the load voltage during the voltage sag will be Vpre-sag.

Pre-sag compensation

This compensation strategy is recommended for the non-linear loads (e.g. thyristor controlled drives) which needs both the voltage magnitude as well as the phase angle to be compensated. In this technique the DVR supplies the difference between the pre-sag and the sag voltage, thus restore the voltage magnitude and the phase angle to that of the pre-sag value Figure 2.9

In-phase compensation

The DVR compensates only for the voltage magnitude in this particular compensation method, i.e. the compensated voltage is in-phase with the sagged voltage and only compensating for the voltage magnitude. Therefore this technique minimizes the voltage injected by the DVR. Hence it is recommended for the linear loads, which need not to be compensated for the phase angle [11,13]. It is clear from the Figure 2.10, that there is a phase shift between the voltages before the sag and after the sag.

Energy optimization technique

In this particular control technique the use of real power is minimized (or made equal to zero) by injecting the required voltage by the DVR at a 90° phase angle to the load current. Figure 2.11 depicts the energy optimization technique. However in this technique the injected voltage will become higher than that of the in-phase compensation technique. Hence this technique needs a higher rated transformer and an inverter, compared with the earlier cases [11,13]. Further the compensated voltage is equal in magnitude to the pre sag voltage, but with a phase shift.

VOLTAGE SAG DETECTION TECHNIQUES

(i) Fourier transform
(ii) Phase Locked Loop (PLL)
(iii) Vector control (Software Phase Locked Loop –SPLL)
(iv) Peak value detection
(v) Applying the wavelet transform to each phase

Out of the techniques mentioned above only the Fourier transform, Vector control and wavelet transform methods provide both the voltage magnitude and phase shift information. PLL method can provide only the phase shift information while peak value detection technique enables to get the magnitude change (voltage sag) information. Hence it is possible to combine one or more techniques mentioned above to obtain accurate voltage sag compensation.

Fourier Transform

By applying Fourier transform to each supply phase, it is possible to obtain the magnitude and phase of each of the frequency components of the supply waveform in addition to the fundamental such as magnitude and phase information of the 5th and 7th harmonic components. This is the advantage of this method compared with other sag detection techniques.

For practical digital implementation 'windowed fast Fourier transform-WFFT' is used which has same features as the Fourier transform [4]. Further this method can easily be implemented in real time control system. The only drawback of this method is after voltage sag has commenced it can take up to one cycle to return the accurate information about the sag depth and its phase. The reason is the calculation method used by WFFT is an averaging technique.

Phase Locked Loop

Generally the DVRs use Phase Locked Loop (PLL) to keep a track of the frequency and the phase angle of the healthy supply voltage, and thereby any change from the normal operating condition can easily be detected [11,31]. Phase locked loop is a closed loop feedback control system, that generates a signal with the same frequency and the phase angle of the input signal. It consists of an oscillator which provides the output signal. The PLL internal function can be categorized as phase detector, variable oscillator and a feedback path. PLL responds to frequency changes and phase angle changes of the input signal by increasing or decreasing the frequency of the oscillator until it is matched with those of the reference input signal.

Simplified PLL is shown in Figure 2.14. The phase angle of the input signal is compared with the feedback output of the oscillator and produces an error signal. The error signal is generated in the form of voltage signal, proportional to the phase angle difference between the input and output. The output of the phase detector consists of harmonic components, thus it has to pass through a low pass filter. But this filtering can introduce transient delays in detecting the voltage sags, which is undesirable [4,2].

The controlled voltage output2 of the loop filter is then feed in to the Voltage controlled oscillator and provides a phase output. This output signal (in the form of a phase angle) is negatively feedback into the phase detector. The output of the oscillator is compared with the input and if the two frequencies are different, the frequency of the oscillator is adjusted to match with the input frequency.

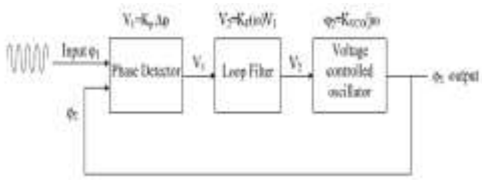

Figure 2.14: Simplified block diagram of a phase locked loop

However reference [3] says that this method to track the phase angle is not accurate and not suitable for fast synchronization. Further with this method it cannot return the sag depth information and difficult to implement in real-time [4]. Hence a more accurate method to detect the phase angle is introduced and referred to as Software Phase Locked Loop (SPLL).

Software Phase Locked Loop (SPLL) / Vector Control

This is an improved method of PLL principal combining a voltage sag magnitude detection technique using the principal synchronous frame voltage quantities. Software implementation of this technique is more accurate, faster detection of voltage sag and can easily be implemented using Digital Signal Processing (DSP). This method is also referred to as vector control technique or simply as the synchronous reference frame model [3,4,11]. It is known that unbalance voltage sags create negative sequence voltages which will rotate in opposite direction to that of positive sequence voltages. When considering the concept of synchronous reference frame, the negative sequence component is assumed to have a frequency of twice the frequency of the fundamental.

When all the sequence components (positive, negative and zero) are present in a voltage waveform it is difficult to track the positive sequence component and also the result can be erroneous [3,11]. Hence the major point of the SPLL technique is it can be used to track only the positive sequence component from the supply waveform and the block diagram is shown in Figure 2.14 [11].

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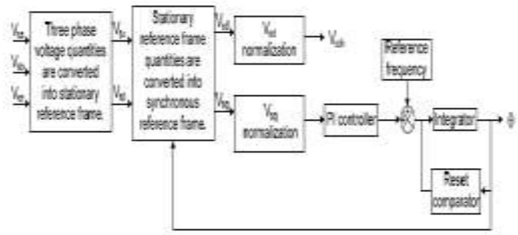

Figure 2.15: Block diagram of a Software Phase Locked Loop

The basic principal behind the operation of SPLL is regulating the Vsqn to zero and to track the phase angle (θ) of the positive sequence voltage of the supply wave form. Initial phase angle information of the supply waveform is given by this θ. Then the voltage output of the SPLL will be equal to Vsd. By comparing Vsd with a set reference point any occurrence of voltage sag magnitude can be detected. The same way by comparing Vsq with a set reference zero the phase angle jump can be detected. This is further explained in Figure 2.15. It is clear from the figure, when Vsqn tends to zero Vsdn is in phase with Vsn (normalized supply voltage), hence any voltage sag can easily be detected by the system.

$$Assumption: \overrightarrow{V_s} = v_{s\alpha} + jv_{s\beta} = \sqrt{\frac{2}{3}}(v_{sA} + \alpha v_{sB} + \alpha^2 v_{sC})$$

In conclusion SPLL principle can be summarized as follows. The synchronous reference frame is locked to the positive sequence of the voltage Vs by the principle of PLL and it produces a voltage vector magnitudes Vd and Vq. The phase angle (theta) used in the synchronous reference frame calculations is used to generate the reference voltage vector [15]. When the system is in locked condition with the normal operating condition Vd becomes same as the voltage vector magnitude and Vq becomes zero. Therefore any disturbance can be identified as they make deviation on the Vd and Vq from their normally operated values. This is how the fast detection normally implemented.

Peak value detection of the supply wave form

The peak value of any waveform is the point at which its gradient tends to zero. This simple phenomenon is used in this technique. The point at which voltage gradient is zero is identified as the peak value of the supply voltage [14]. It is compared with a preset reference voltage. If the voltage difference between the supply and the reference voltage exceeds a specified value (eg. 10%) then the DVR starts operating (DVR inject the difference voltage). The voltage gradient can be calculated as follows

$$\text{Voltage Gradient} = \frac{V_t - V_{t-\delta t}}{\delta t} \qquad Eq.\ 2.4$$

v_t is the voltage at time instant t and $v_{t-\delta}$ is the voltage at time $t-\delta t$ where δt is a small time step.

As in reference [14], the drawbacks of this method are the time delay (up to 0.5 sec.) in getting the sag depth information and the noise that would affect the measurements severely. Further to get the phase shift information a reference waveform is needed which has to be generated separately.